Chapter 5
Shellfish Aquaculture

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In the scheme of global aquaculture production, freshwater finfish dominate, followed by aquatic plants, mollusks, crustaceans, and marine fish. Among marine species in culture, shellfish are the dominant group with annual harvests exceeding 13.1 million tonnes worldwide, compared with 5.3 million tonnes of crustaceans, and 3.4 million tonnes of diadromous and marine fish. Crustaceans (mostly shrimp) lead in terms of the dollar value of production at over US$24.1 billion per year, but molluscan shellfish are not far behind with annual harvests just under US$12.9 billion (FAO 2009). Production of cultured mollusks continues to expand at a remarkable rate with global landings increasing 42% in the ten-year span from 1999 to 2009.

The overwhelming majority of shellfish culture occurs in China and the Asian Pacific (80% of the value and over 90% of the biomass). For the past twenty years Asia's production of oysters has doubled about every ten years while their clam production has nearly tripled every ten years. A plot of international production makes Asia's dominance in aquaculture readily apparent (fig. 5.1). Western Europe, North America, and Oceania (Australia, New Zealand, and the Islands of the South Pacific) are all significant shellfish producers, but Africa, India, and the Middle East so far have relatively small shellfish culture industries.

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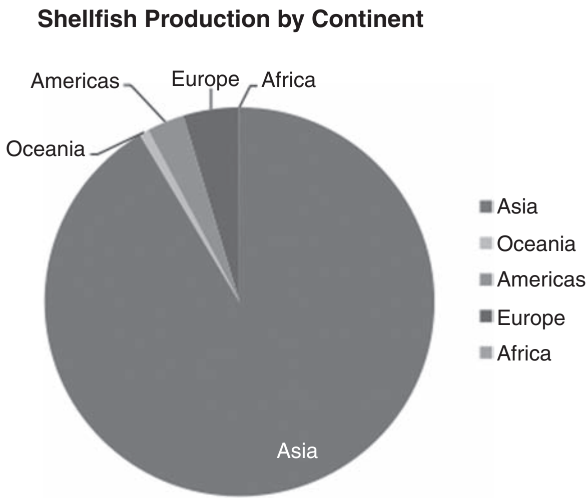

Figure 5.1 Shellfish production by continent (FAO 2009).

5.1 Major species in culture (oysters, clams, scallops, mussels)

The FAO (2008) subdivides molluscan shellfish production into seven categories: oysters, clams (including cockles and arc shells), scallops, mussels, "miscellaneous mollusks," freshwater mollusks, and abalones (including winkles and conchs). The world harvest of cultured oysters in 2006 totaled 4.7 million tonnes. The FAO lists fourteen species of oysters in culture, but the most significant contributor by far is the Pacific or Japanese oyster, *Crassostrea gigas*, which alone accounts for 97% of the world oyster production.

The American or Eastern oyster, *Crassostrea virginica,* ranks second, accounting for 1.4% of world production; followed by the Suminoe oyster, *Crassostrea ariakensis,* with 0.5%; and the European flat oyster, *Ostrea edulis,* and the Sydney rock oyster, *Saccostrea commercialis,* each with 0.1%. These are the principle oyster species in culture by volume, but there are dozens more oyster species in culture around the world.

World clam culture produced 4.3 million tonnes in 2006 (FAO 2008). There are relatively few species of clams currently being produced in culture, the most significant by far being the Manila or carpet clam, *Ruditapes phillipinarium*. China's production of this one species exceeds 3 million tonnes a year. In the United States in the 1930s, Manila clams were accidentally introduced in the Pacific Northwest with a shipment of Pacific oyster seed and the Manila clam is now a major aquaculture species from California to British Columbia with regional annual harvests of 6,000 tonnes valued at over US$25 million. In Europe, overfishing and irregular yields of the native (European) grooved carpet shell, *Ruditapes decussatus,* led to imports of *R. philippinarum* into European waters. European countries now grow 58,000 tonnes of Manila clams, slightly eclipsing their wild harvest fishery.

The constricted tagelus, *Sinonovacula constricta,* supports annual harvests of 680,000 tonnes in Asia making it the second most popular cultured clam species. The northern quahog or hard clam, *Mercenaria mercenaria* is grown in the United States and Canada where annual harvests exceed 38,000 tonnes. Most of this production has developed in the past ten years with Virginia and Florida being the biggest producers. Also of note because of its impressive size is the geoduck, *Panopea abrupta*. It is the largest known burrowing bivalve weighing as much as 3.2 kg, with a shell measuring up to 18- to 23-cm long and siphons that extend up to 1.3 m. These clams are native from Baja California to Alaska, burrowing as deep as a meter or more in intertidal or subtidal sands. Growers are trying to expand production of this species to meet the demand from lucrative Asian markets. The geoduck can live over 100 years, but farmers typically harvest them after only four to seven years.

World scallop harvests totaled 1.4 million tonnes in 2006 (FAO 2008). Many species of scallops have been used in aquaculture because of their high fecundity, rapid growth, and the high value of their meats. Scallops are typically grown in lantern nets or by ear-hanging, but production from these labor-intensive methods is dwarfed in localities where growers are able to "ranch" the scallops by dispersing seed on the bottom. Countries with inexpensive labor, such as China, continue to employ massive suspended culture operations, accounting for over 81% of the world scallop production—primarily the Japanese scallop, *Patinopecten yessoensis,* and the northern bay scallop, *Argopecten irradians*. There is also substantial scallop production in Japan, Korea, and the Russian Federation. Lesser scallop producers include Peru and Chile (*Argopecten purpuratus*), Canada (sea scallop, *Placopecten magellanicus*), and the United Kingdom (Queen scallop, *Chlamys opercularis*).

The world mussel harvest totals 1.9 million tonnes and is spread around the globe (FAO 2008). China produces 39% (primarily the green shelled mussel, *Perna viridis*), Thailand 14% (*Perna canaliculus*), New Zealand 5% (*P. canaliculus*), and Spain 12% (Mediterranean mussel, *Mytilus galloprovincialis*). The blue mussel, *Mytilus edulis,* representing 8% of world harvest, is raised primarily in western European nations with contributions from Canada and the United States.

The FAO's category of "miscellaneous mollusks" lists harvests of 1.3 million tonnes. There are dozens more bivalve species being grown in significant numbers, with many more being studied and evaluated for aquaculture. Annual harvests of abalones, winkles, and conchs total 367,000 tonnes. Freshwater mollusks are a minor player on the world stage with production totaling only 154,000 tonnes, but that number has grown tenfold in the past five years.

5.2 History

The history of the development of shellfish aquaculture reveals that culture efforts only become significant when natural stocks become depleted from overfishing. China and Japan are generally believed to be the first nations to

practiced have shellfish culture. In China the first efforts are thought to have started 2,000 years ago during the Han Dynasty (Nie 1982). Early growers simply drove wooden stakes or provided piles of rock or shell to attract sets of oysters in areas that were otherwise too muddy to grow oysters. These relatively primitive techniques remained virtually unchanged for hundreds of years, and production didn't really take off until 1950s. Subsequent production in China doubled every ten years until the 1980s when it really exploded. Between 1980 and 1990 production increased fourfold to 1.8 million tonnes, and in the next decade production again increased fourfold, reaching 7.5 million tonnes by 2000 (FAO 2009). Japan was one of the first nations to develop intensive shellfish culture techniques. Spat collection efforts were recorded as early as the seventeenth century (Lou 1991). Early efforts involved fencing off intertidal flats with woven bamboo to eliminate predators, while inside these enclosures, bamboo stakes, rocks, and shell were planted in rows during spawning season to provide suitable substrate for larval oysters to attach. Once the spat were of suitable size the screens could be removed, and after two to three growing seasons the oysters were harvested.

In the 1920s Japanese growers became some of the first to experiment with hanging culture techniques (Nie 1982). Oyster spat were still collected on intertidal racks, but they were moved to deeper water in various enclosures that were suspended under rafts or on longlines. Suspended culture, was shown to increase growth rates and eliminate mortality from benthic predators while allowing growers to use areas that were not suitable for bottom culture (Imai 1978). Yields increased dramatically with suspended culture and time to harvest could be cut by nearly a full year. Scallop growers using hanging culture in Hiroshima Bay claim some of the highest production densities on record, with up to 20,000 kg/ha of meat per year (Lou 1991). Japanese scallop culture really took hold with refined methods for spat collection and the development of hanging culture methods (ear hanging and lantern nets) in the late 1960s. In ten years' time cultured harvest eclipsed wild landings, propelling Japan into the position of top scallop producer in the world. Successful spat collection efforts also led to huge increases in bottom plantings with commensurate increases in yields (Lou 1991).

Around the same time wild scallop landings started to decline in China. By borrowing spat collection technology and lantern net design from the Japanese, scallop culture was initiated in China in the late 1970s. Seed supply issues were resolved with massive investments in hatcheries and improvements in spat collection, and the industry took off (Lou 1991). By 1985 production was up to 10,000 tonnes and by 1992 China surpassed Japan as the number-one producer of scallops, with harvests of 338,000 tonnes. In 1996 China reported cultured landings totaling 81% of the world's scallop production (FAO 2007).

Mussels became important in Spain when farmers began culturing them at the beginning of the twentieth century. The first mussel culture developed near the Iberian Peninsula in the early 1900s by placing poles in the sediment to catch spat (FAO 2006). Raft culture of mussels was introduced in the Galician region in 1946 and within a few years production had increased sharply (FAO 2006).

French and British oyster culture efforts began in the 1800s. In 1866 the famous British biologist Thomas Huxley was commissioned to investigate the causes of the 30 year decline of the oyster fishery. He declared that the preposterous regulations hampering the various fisheries should be abolished because the supply was "inexhaustible." Huxley reasoned that regulations such as "closed seasons" were ineffective at controlling over-dredging because they did not control the fishing effort when the restrictions were lifted. In his 1883 inaugural address to the London Fisheries Exhibition he conceded that oysters "may be exhaustible" and recommended that the "State can grant a property in the beds to corporations or to individuals whose interest it will become to protect them efficiently. And this I think is the only method by which fisheries can be preserved" (Blinderman 2008). At the time, oyster culture consisted simply of holding oysters that had been dredged, but were too small for sale, in wooden "barks" that suspended the oysters in protected tidal areas.

In France in 1869 a boatload of Portuguese oysters, *Crassostrea angulata,* was inadvertently dumped near the mouth of the Gironde River. They grew well and were found to be more durable than the native *Ostrea edulis*. They became the foundation of much of France's oyster production for the next 100 years, until the decision to introduce *C. gigas*.

In the United States oysters were a huge source of easily accessible protein from the time of the early settlers until the late 1800s when harvests began to peak. The completion of the Transcontinental Railroad in 1869 and the invention of steam-powered boats in the 1880s led to rapid depletion of vast beds of oysters in the mid-Atlantic and New York waters. In the 1860s oyster growers started taking schooners full of oysters and seed from these populations to be bedded on thousands of acres of private leases in Long Island Sound and Narragansett Bay, where they would fatten and grow quickly (Kurlansky 2006).

In 1884 the "Oyster Panic" hit New York when cholera outbreaks (a disease attributed to filthy living conditions in Manhattan's slums) resulted in a number of deaths among rich oyster eaters. That same year Koch proved sewage-related bacteria was the cause of typhoid and by 1890 Pasteur's "germ theory" had become accepted doctrine (Kurlansky 2006). At the time, every major city was dumping millions of gallons of untreated sewage and horse manure into estuaries, and deforestation was leading to siltation of many prime oyster beds. The advent of running water and the invention of the flush toilet at the turn of the century made a severe problem much worse. The first oil refinery was built on the East River in 1872 and shortly thereafter oil spills and discharges made oysters and fish taken from estuaries near many major cities taste like oil. None of this was good for the oysters or their delicate larvae.

In 1925 the surgeon general mandated the formation of the National Shellfish Sanitation Program in response to the decades of outbreaks of typhoid fever related to the consumption of raw oysters (Yuhas 2002). Shellfish-related illness continued to plague the industry for decades, but advances in sewage treatment, monitoring, and restrictions on ocean dumping have greatly diminished the risk.

In the United States, overharvesting, habitat destruction, and the oyster diseases MSX and Dermo that hit the mid-Atlantic states in the late 1950s and

1990s, respectively, decimated Eastern oyster populations. Natural populations were reduced to a tiny fraction of historical levels. More recently, interest in oyster aquaculture has been stimulated by a renaissance in oyster consumption at trendy raw-bars across the country.

Development of shellfish hatchery techniques became the focus of research when natural oyster recruitment along the Eastern Seaboard became unpredictable in the early 1900s. Joe Glancy working at Blue Points Company on Long Island in the 1940s did pioneering work that was later refined by Victor Loosanoff and Harold Davis at the National Marine Fisheries Service Lab in Milford, Conn. (Carricker 2004; Matthiessen 2001). A prerequisite for the development of successful hatchery production was the refinement of techniques to produce microalgal food. Glancy (who was building on the work of W. F. Wells) described a simple method of coarsely filtering seawater down to 5 or 10 μm and introducing some fertilizer to stimulate algal growth. After a few days of sunlight, a rich broth of mixed-algal species was often the result. The so-called Wells-Glancy method was the primary way to produce micoalgal shellfish food for decades. Unfortunately, the quality of the algae produced using the Wells-Glancy method is unpredictable and prone to contamination (Carricker 2004). Robert Guillard later developed techniques to isolate and grow axenic, bacteria-free, single-species cultures and developed a collection of hundreds of species from around the world. Cultures from his collection, and others that have followed, are used by hatcheries around the world.

5.3 Biology

The vast majority of shellfish in culture are bivalves from the phylum Mollusca. These are relatively primitive organisms that feed by passing large volumes of water across a fine ciliated gill to filter out microscopic plants and organic particles. Like most filter-feeders, they are omnivorous consumers of small particles, including microalgae (diatoms and flagellates), organic detritus, bacteria, viruses, and small protists, (collectively referred to as "organic seston"). Mollusks are typically infaunal or epifaunal and are mostly sedentary. Scallops and razor clams have been known to swim significant distances in search of food or to avoid predators, but clams rarely move more than a few centimeters a day. Oysters have evolved to spend their entire life cemented in one place.

Shellfish are classic r-strategists, meaning that each adult is capable of producing large numbers of larvae (up to several million), ranging from 60 to 250 μm in diameter (Mackie 1984). Such high fecundity means shellfish are able to maintain stable populations, even if only one in a million survives to reproductive age; and it also means that under optimal conditions they can colonize new habitats opportunistically, sometimes at densities so great that they smother each other.

Shellfish larvae are free-swimming plankton for the first two to three weeks of their lives. Under a microscope, most shellfish larvae look like a typical clam,

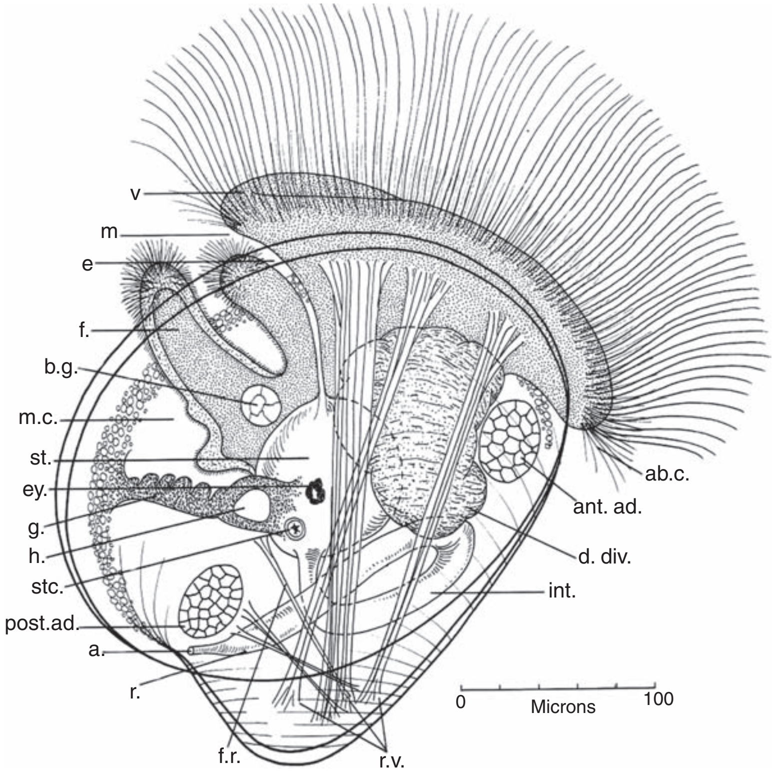

Figure 5.2 Diagram of veliger larvae. Abbreviations in diagram are (a.) anus; (ab.c.) aboral circle of cilia; (ant.ad.) anterior adductor muscle; (b.g.) byssus gland; (d.div.) digestive diverticula; (e.) esophagus; (ey.) eye; (f.) foot; (f.r.) foot tractor muscles; (g.) gill rudiment; (h.) heart; (int.) intestine; (m.) mouth; (m.c.) mantle cavity; (post.ad.) posterior adductor muscle; (r.) rectum; (r.v.) velar retractor muscles; (st.) stomach; (stc.) statocysts; (v.) veulum. Figure from Paul Galtsoff (1964).

but with a transparent shell and ciliated vellum that is a combination feeding structure and propulsion mechanism (fig. 5.2). Capable of swimming only a few centimeters per minute, they ride the tides and can be dispersed for many kilometers before settling.

After the larvae develop, they seek an appropriate place to settle and spend the rest of their lives. Infaunal species such as clams seek sand or muddy bottom while oysters look for firm substrate (preferably shell) to which they can cement themselves. Mussel, clang and scallop larvae secrete an epoxy-like byssal thread that hardens on contact with seawater, allowing larvae to fasten themselves to firm structures, usually off the bottom and away from predators such as crabs and starfish.

Once the larvae find an appropriate place to settle they undergo a complex metamorphosis and take on the adult morphology. Under proper conditions they will grow rapidly from about 250 μm at settlement to several millimeters in a few weeks. Under ideal conditions fast growing species can reach 7 cm or more

in the first growing season and will be able to reproduce the following year, with some species living only two years (e.g., *Argopecten irradians*).

5.4 Culture basics

Shellfish aquaculture is much like other agriculture in that it involves planting and nurturing seed; protecting the crops from predators, disease, or storms; harvesting the crop; and marketing the perishable product. There are, however, unique challenges tied to working on the water that add several degrees of difficulty. Monitoring the crop condition, growth rate, and survival through the lens of several meters of water usually requires hauling cages or donning scuba gear. Aquaculture also requires the prospective grower to obtain exclusive use of a public resource that has many other user groups vying to protect their interests. In today's world, all this must be done under the watchful eye of environmental groups that are increasingly wary of any new potential perturbations or stresses on the fragile, inshore marine ecosystem. Unlike terrestrial agriculture, which has developed over centuries, shellfish aquaculture is relatively new, and the scientific underpinnings that guide growers' actions have mostly been developed in the last 50 to 100 years. Growers are still refining techniques to surmount the many challenges that arise. Given the tremendous spatial and temporal variability of the marine environment, it is common that techniques that work well in one area are ineffective a short distance away.

In its essence, shellfish aquaculture involves two, sometimes conflicting, goals: (1) protecting the animals from predators while (2) ensuring an ample supply of food. Shellfish farmers have developed dozens of different ways to grow shellfish while balancing these two objectives. Because each species has slightly different requirements and each growing area poses a unique set of challenges, no single culture method will work in every growing area.

There is an amazing array of potential predators that consume shellfish, especially when the shellfish are small. Consequently, if a grower leaves seed unprotected it is not uncommon for predators to consume most of the crop. Predators can include birds, starfish, crabs, fish, and predatory gastropods such as whelks or oyster drills. A flock of diving ducks can pick a mussel raft clean in a few days, while roving populations of starfish can annihilate whole shellfish beds in a matter of weeks. Many species of crabs feed voraciously on shellfish and juveniles are especially vulnerable. The diminutive sand shrimp (*Crangon* sp.) can feast on newly set shellfish, while a single blue crab (*Callinectes sapidus*) can consume hundreds of clam seed in an hour (Arnold 1984). In response, growers have devised a wide array of protective enclosures.

The ideal environment for shellfish is one that has ample available food and protection from predators. Whereas growth in a solitary bivalve is primarily determined by the concentration of particulate food in the water, a dense population of shellfish will rapidly consume all of the food in the immediate area unless there is a good current to replenish the food supply. For filter-feeders being grown at commercial densities on an aquaculture farm, current speed is

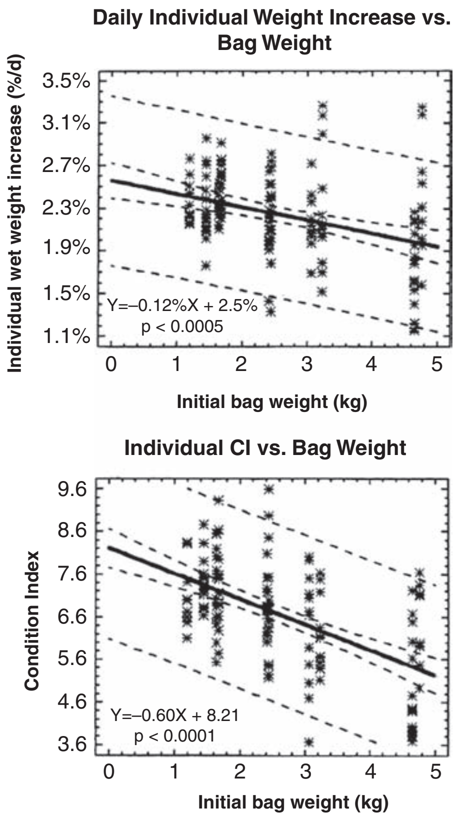

Figure 5.3 Stocking density versus growth and condition index in individually tagged oysters after six weeks. Growth rates (upper graph; percent increase in weight per day) and condition index (lower graph) are plotted against initial stocking density of the bag. Linear regression formulae are shown with each line plotted with 95% confidence limits (inner dashed lines) and 95% prediction limits (outer dashed lines). From Rheault and Rice (1996).

usually just as critical as food concentration in determining food availability (Peterson *et al.* 1984).

The product of current speed and food concentration is called "seston flux" and this number determines how densely a grower can stock the shellfish before food competition starts to limit growth (Grizzle & Lutz 1989). In any given location growers must experiment with different stocking densities to determine the optimal production density. At higher stocking densities growth rates will decline because the shellfish are experiencing local food depletion and suboptimal food availability (Rheault & Rice 1996; fig. 5.3). Lowering the planting density will reduce stress, improve the condition index (the ratio of meat weight to size), speed growth, and reduce the time to harvest. Shortening the time to harvest in turn reduces the amount of gear needed for multiple crops and lowers the risk of mortality.

Growers are often faced with an economic dilemma. At lower stocking densities, growers must deploy and maintain much more gear in order to produce

the same biomass, which dramatically increases unit production costs, so there is a clear economic trade-off. At some point, all growers need to calculate the optimal production density for their farm by balancing the increased costs of more gear stocked at lower densities with the benefits of low stocking densities (reduced stress, lower mortality, faster growth, shorter time to harvest, and better meat yield). This exercise needs to be repeated for every growing area, for every species, and for different stages of growth because the curves will have different shapes and inflexion points for each (Rheault & Rice 1996). The curves will also be displaced by changes in food quality, by monthly changes in tidal velocity, and seasonal changes in temperature. In intensive production systems the cost of buying and maintaining additional gear to maintain low densities will have a profound impact on the economics of production. All the benefits of lowering densities described above may be lost if the grower is unable to properly maintain the additional gear.

5.5 Extensive versus intensive culture

In their efforts to protect shellfish from predators, growers have resorted to various predator barriers such as cages, mesh bags, or netting. These techniques are considered "intensive culture." By growing clams under netting, or oysters in mesh bags or cages, farmers are often able to reduce predation losses to near zero. These approaches, however, require increased capital investment and involve tremendous amounts of labor to maintain and to clean the gear. The mesh of the netting (and any firm substrate left in the marine environment) quickly becomes fouled by a remarkable variety of fouling organisms. Fouling restricts the flow of water to the crop, which in turn reduces the availability of food for the shellfish, resulting in slower growth and poor condition.

The alternative to using predator barriers is to take a more natural approach such as free-planting seed on the bottom. These extensive culture techniques accept a certain level of losses due to predation, compensating with sheer numbers and maintaining profitability by keeping costs low and minimizing inputs of energy, capital, and labor.

Sometimes it is difficult to draw a line between a well-managed fishery and extensive aquaculture. The efforts of extensive farmers may be limited to enhancing natural spat collection or rudimentary predator control. Conversely, several wild shellfisheries are augmenting their catch by utilizing culture techniques such as hatcheries, spat collection, planting, and rotational harvesting (Booth & Cox 2003). The line is often drawn based on the fact that growers lease the bottom from which they harvest, but this distinction is subtle enough to confuse both regulators and statisticians.

For example, there is significant debate as to whether the substantial oyster landings of Connecticut, Louisiana, and Mississippi should be considered cultured or wild harvested. These growers use techniques that are little changed since the late 1800s. Typically, either the growers or the state managers (or both) spread tons of clean shell, called "cultch," in areas (often public) where

they know larvae will be abundant. Once the young oyster spat are established on the cultch, they are harvested and spread on leased beds for growout until the oysters reach market size. Growers move the seed to different beds depending on the density, size, or growing needs of the oysters. Some leaseholders may engage in starfish "mopping" or crab trapping to reduce predation losses. Because the level of husbandry varies greatly from grower to grower, the federal government continues to struggle with the legal definition of "cultured" in these multimillion-dollar fisheries.

In reality, no clear lines can be drawn separating sustainably managed wild shellfisheries, extensive culture, and intensive culture. Instead there is a broad spectrum of approaches, each designed to take advantage of local conditions, the biology of the species, the various predators, labor costs, materials costs, and the economics of production. Intensive culture usually involves hatchery production, nursery structures such as upwellers or raceways, and growout strategies involving predator barriers such as netting, cages, racks, and bags. Extensive culture typically relies on wild set (sometimes enhanced using spat collectors); growout efforts are limited to spreading the seed on the bottom and very little is spent on culture gear or predator control. The lines become blurred when intensive culture systems rely on wild spat collection or when extensive systems use hatcheries or nurseries. Such hybrid approaches are common.

5.6 Spat collection: hatchery, nursery, growout

Shellfish aquaculture can be subdivided into three components based on the life cycle needs of the species in culture and the culture techniques used by the grower: hatchery (or spat collection), nursery, and growout. The lines between these three steps can be blurred, depending on the species and the culture techniques. Some growers will move seed as small as 1 mm or less from a hatchery into their nursery systems, but most will wait until the seed are 5 to10 mm. Nursery culture techniques such as upwellers, raceways, and spat bags can theoretically be used for larger animals, but at some point growers typically transition to a more economical growout method. Growout methods vary widely from extensive bottom planting to intensive methods involving rafts, lantern nets, or various types of racks and bags.

5.6.1 Spat collection

The first step in any culture effort is the acquisition of juveniles. Most early shellfish culture efforts concentrated on improving spat collection and the survival of tiny, post-set juveniles. Shellfish larvae are microscopic and free-swimming for the first weeks of their life and they are a terrific food for larval fish, crustaceans, and gelatinous zooplankton. Natural mortality rates for larvae and post-set juveniles are astronomical, so anything that can be done to attract the settlement

of larvae and improve the survival of these delicate early life stages can have a dramatic impact on survival rates and harvest numbers.

Late-stage larvae will begin to seek the bottom and sample the substrate looking for ideal conditions in which to spend the rest of their lives. Some larvae can delay settlement for days while their instincts drive them to seek the right combination of environmental cues that give them the best chance to survive long enough to make their own contribution to the gene pool. Some species have evolved to seek out brackish intertidal waters to avoid certain predators, while some require subtidal or deeper waters. Clam larvae typically seek out sandy or muddy bottom, while oysters typically seek shell or other firm substrates to which they can cement themselves; scallops typically seek grasses or other off-bottom substrates.

Many larval and juvenile shellfish species possess a byssal gland that secretes tiny adhesive threads allowing them to adhere tenaciously to various objects. In the hard clam (*M. mercenaria*) this ability is lost once the seed grow beyond a few millimeters, while most scallop species still use byssal threads until they are a centimeter or more in length. Mussels never lose the ability to secrete strong byssal threads.

The earliest aquaculture efforts consisted of attracting larvae by simply providing the proper conditions to enhance natural settlement. Early naturalists observed oysters setting on almost any firm substrates in protected waters, and found that by placing ceramic tiles, shell, or even sticks of wood in the appropriate waters they could collect oyster seed in great quantities. When natural populations of shellfish dwindled due to overharvesting and disease, fishermen and resource managers began to experiment with various spat collectors to enhance the natural set. By testing different materials placed at different times of year they were able to determine that oysters prefer clean shell placed in the water shortly before peak settlement. Substrates placed in the waters too early became fouled with other organisms. They also discovered they could greatly enhance oyster sets by coating twigs or ceramic tiles with cement because the larvae detect the lime, which resembles shell.

Similarly, naturalists observed that scallop larvae seek eelgrass or similar vertical structures to which they can attach themselves via a byssal thread. It was discovered that mesh bags stuffed with burlap, polypropylene, or old monofilament line and suspended in various locations could reliably catch scallop sets. Further experiments have resulted in refinements in the types of fibers used, as well as in the ideal timing and location for the placement of spat bags so that yields of several hundred spat per bag are not uncommon. Most sea scallop farms still rely on spat collector bags, while nearly all of the mussels cultured around the world are the product of spat collectors, which consist of specially designed fuzzy ropes. Some mussel spat are still scraped from rocks to fill growout mesh tubes called "socks," and, remarkably, the substantial New Zealand green mussel industry still relies on wild spat collected from seaweed that predictably washes ashore on a certain beach each year.

Unfortunately, wild spat sets are not always reliable. In the late 1800s, oyster growers in Connecticut and Long Island had built a multimillion-dollar industry

based on the placement of millions of bushels of shell in established setting grounds in estuaries along the coast. When spat falls failed for four consecutive years starting in 1912, the industry nearly collapsed. Eventually, researchers developed hatchery techniques in an effort to revive the industry and stabilize production. Historically, investments in hatcheries have been sporadic because hatchery production is easily dwarfed when environmental conditions align to favor a strong natural set.

5.6.2 Hatchery methods

Hatchery techniques were initially developed for shellfish in the 1940s by Joe Glancy working at Blue Points Company on Long Island and were later refined by Victor Loosanoff, Harold Davis, and Robert Guillard at the National Marine Fisheries Service Lab in Milford, Conn. (Carriker 2004). A prerequisite for the development of successful hatchery production was the refinement of techniques to produce significant amounts of single-celled algal food for the broodstock and subsequently for the larvae and post-set spat. Glancy (who was building on the work of W. F. Wells) described a simple method of coarsely filtering seawater down to 5 or 10 μm and introducing some fertilizer to stimulate algal growth. After a few days of sunlight, a rich broth of mixed algal species was often the result. The so-called Wells-Glancy method was the primary way to produce micoalgal shellfish food for decades (Carriker 2004).

Unfortunately, the quality of the algae produced using the Wells-Glancy method is unpredictable because there is no control over which species dominate the brew. Not all algal species are good shellfish foods because some species are indigestible, noxious, or even toxic. Also the Wells-Glancy method is prone to contamination by various flagellates and protists that can multiply almost as fast as the algae and can eat most of the desirable small cells.

5.7 Cultured algae

Robert Guillard developed techniques to isolate and grow axenic, single-species cultures and developed a collection of hundreds of species from around the world (Guillard 1975). Several single-celled algae species are good bivalve foods, easily digested, and provide a balance of critical essential amino acids, proteins, fatty acids, and carbohydrates needed to promote growth (Webb & Chu 1983; Wikfors *et al.* 1992). Hatcheries sterilize large volumes of seawater using heat, chlorine, or microfiltration so they can reliably produce the large volumes of algae needed to commercially produce shellfish. These can be produced in large batches or semi-continuously by harvesting a percentage and replenishing the sterile media daily.

Modern hatcheries typically will try to have several algal species in culture so they can offer a mixed diet and have different cell sizes and nutritional profiles available to meet the dietary needs of different life stages of larvae, post-set and

broodstock. More often than not, the key to good quality egg production and good larval survival is related to the quality, variety, and volume of algal food provided.

The economics of microalgae production remains one of the roadblocks to the development of land-based culture systems for filter feeders. Microalgal production costs can be as high as US$200 per dry kilo because of the costs of labor and the expense of sterilizing seawater (Persoone & Claus 1980). More recently, systems have been developed to automate continuous-flow systems (SeaCAPS, UK), and microalgae can be purchased in paste form (Instant Algae, Reed Mariculture, Campbell, CA). Efforts to supplement or replace microalgae with less expensive microparticulate foods such as yeasts or rice starch have not been very successful (Epifanio 1981). The nutritional profiles and hydrodynamic properties of the particles are critical to their acceptance and utilization by filter feeders (Webb & Chu 1983; Wikfors *et al*. 1992). The food demands of shellfish increase exponentially as they grow in length, so it becomes imperative to start feeding the spat with natural algae as early as possible.

5.8 Spawning

Bivalve spawning is usually simple to induce if the brood stock are properly conditioned and fully ripe. Most species can be induced to ripen by simulating late spring water temperatures and providing ample algal food for four to six weeks. Many bivalve species are hermaphroditic, producing both eggs and sperm, but typically they do not release both at the same time because survival of self-fertilized eggs is poor. Many bivalve species are protandric hermaphrodites, starting life as a male, but developing ovaries as they get larger; however, in lean years the sex ratio is likely to favor males because it takes more energy to produce eggs than sperm.

Depending on the species and size of the individual, it is common for a ripe female to produce 3 to 30 million eggs in a single spawn. In subtropical environments they can do this several times a year. As much as 30% of the body weight of bivalves is gonad, and spawning is so energetically costly that it leaves the adults thin, weak, and prone to mortalities.

Many temperate populations only spawn once a year and have evolved strategies to synchronize the release of gametes to optimize their breeding success. While several species of bivalves remain active in winter temperatures (e.g., *Mytilus*), some are no longer able to feed when water temperatures drop below 7 to 10°C (e.g., *Crassostrea* and *Mercenaria*). Their digestive enzymes no longer function and filter-feeding ceases for several months a year (Brock *et al*. 1986). Their metabolism slows and they only need to open their valves briefly for respiration. When waters warm in the spring most of their energy is devoted to building up their gonad, and following a string of warm days the entire population will spawn at once.

Most shellfish release their eggs and sperm into the water, where they mix and fertilize. There are a few species of "brooders" (*Ostrea* sp.) that retain the

larvae in the mantle cavity, allowing the larvae to swarm around the gill for the first weeks of development (Chaparo *et al.* 1993). Most temperate species can be induced to release eggs and sperm with thermal shock by raising and lowering the water temperature by 5 to 10°C. If this fails, spawning can often be induced chemically by adding a few drops of sperm to the water. Spawning has also been induced with injections of neurotransmitters such as serotonin. Sperm and eggs can also be obtained by "strip spawning," which involves macerating the gonad with a razor blade and filtering out the chunks of tissue. Typically, naturally released eggs will have much better survival rates than those obtained by these more drastic measures.

When fertilizing batches of eggs, hatchery operators need to exercise care. Shortly after a single sperm penetrates the egg, a change on the cell surface makes it refractory to additional sperm; however, in certain species of shellfish this transformation takes longer than in higher organisms. If sperm cells are too concentrated, several may penetrate a single egg at once (polyspermy). When this happens, abnormal development and mortality can be expected. Proper dilution and judicious additions of sperm are required to ensure that a good percentage of the eggs are fertilized, but not too many are fertilized more than once (Bricelj 1979).

5.9 Larval development

Fertilization takes place quickly, and at proper temperatures cell division begins in under an hour. In 12–18 hours the embryos are called trochophore larvae, which appear to be ciliated balls, swimming in lazy spirals. After 24 hours "D-stage" larvae are visible. These larvae look like a microscopic clam, starting out at about 60 to 110 μm in diameter, developing in two to three weeks from veligers to pediveligers (fig. 5.2), and increasing to 150 to 250 μm or larger at the time of settlement.

For the first few weeks of their lives, most bivalve larvae are free-swimming and planktonic. The shell is transparent, revealing the heart pumping and algal cells being processed in the gut. Veliger larvae swim using the vellum, which is a ciliated organ that also captures algal cells. Veligers feed on single-celled algae, typically flagellates and diatoms of 1 to 3 μm in size. Algal concentrations need to be maintained at around 10,000 cells/ml, as veligers will starve if densities are too low and will not thrive if concentrations are too high.

Larvae are typically reared in batches of 1,000 to 100,000 liters or more at densities from 5 to 25 per ml. Operators usually drain the tanks through a very fine-mesh sieve every other day and refill the tank with filtered seawater and algae. More recent experiments have shown that larvae can be grown in much higher densities in flow-through systems by placing a fine filter over the drain. Gentle aeration is provided to stir the tank, otherwise the larvae tend to swarm together. Growers generally try to produce seed in early spring so they can be moved out of the hatchery in early summer to take advantage of the entire

growing season. This means incoming water needs to be heated to maintain good growth.

5.10 Setting

After two to three weeks, the larvae develop a foot and start investigating the bottom of the vessel in preparation for settlement. Hatchery operators will present these pediveliger larvae with an appropriate substrate (e.g., for oysters this is usually crushed shell). Clams and scallops will often set on the bottom or sides of the vessel. Once the larvae are no longer swimming in the water column, they need to be spread out horizontally so they are not overcrowded. Setting trays are the best way to help the larvae survive the metamorphosis from free-swimming larvae to sessile spat. Setting trays consist of a fine-mesh screen that is stretched taut and floated or suspended in a large tank. Water (and algae) is gently pumped into the top of the tray and it flows out through the screen. To keep oysters from setting on the sides of the setting trays, growers will often coat the sides with a thin layer of wax or Vaseline.

Post-set mussels, scallops, and clams will start to produce byssal threads and they will glue themselves to the tank, each other, or almost any other firm substrates offered by the grower. They can release the byssal thread if they decide they need to move. Negatively geotactic scallops will sometimes climb up to the water surface where they need to be gently brushed back into the water. These "escape" attempts can be prevented by offering scallops an eelgrass mimic such as weighted tufts of nylon, polypropylene, or burlap fiber. Post-set clams will attach their threads to each other, forming a mat that must periodically be sieved gently to break up clumps so the clams don't smother each other.

Post-set shellfish (referred to as "spat") are highly susceptible to bacterial and protozoan infections, predators, and fouling organisms. Their shells are fragile and they need to be handled delicately. Given proper food and growing conditions they will grow rapidly, but getting good larval survival through metamorphosis and the early nursery stages can be difficult. Young shellfish are ravenous feeders whose food demands grow exponentially as they increase in size. Feeding millions of spat once they get to be a few millimeters in length requires hundreds of liters of microalgae. The food needs to be the right species, harvested in good condition, and offered at the right concentrations (~25,000 cells/ml).

As soon as possible, hatchery operators try to move away from static systems (draining the tank and changing water every other day) to continuous flow systems in an attempt to flush away waste and maintain good water quality. Unfortunately, this brings a new set of problems as precious food gets flushed down the drain and large volumes of water must be heated and filtered. Some of the cultured algal food can be supplemented with natural food by pumping raw seawater, but in early spring ambient phytoplankton concentrations are still typically low and the water needs to be heated to maintain good growth. Also, raw seawater needs to be coarsely filtered to remove potential predators,

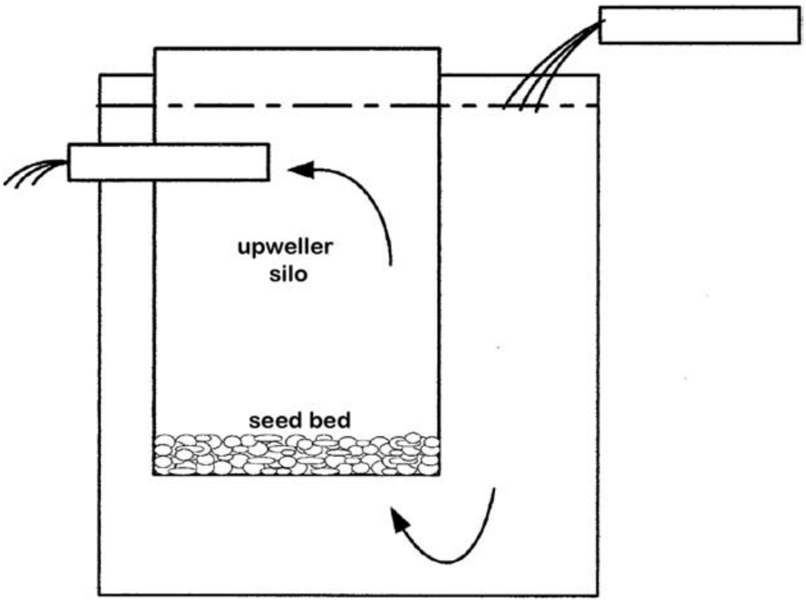

Figure 5.4 Diagram of an upweller. Figure courtesy of Robert Rheaulf.

competitors, and fouling organisms, as well as detritus and algal cells that are too large to eat. Hatchery operators often use 5 μm or 10 μm bag filters, which require regular cleaning.

The most common way to rear post-set juveniles is to use upwellers and downwellers. A screen fine enough to retain the spat is stretched taut and floated or suspended in a large tank while water is drawn upward or downward through the screen (fig. 5.4). Each screen-bottom vessel is referred to as a "silo" because it is often fashioned out of PVC pipe, but square silos are also common. Smaller seed are usually grown in downwellers because the seed are so light that the upflow current in upwellers can carry them up and out the drain. Once seed grow over 1 mm, they have enough mass to be placed in upwellers, but it is still prudent to place a screen over the drain. In upwellers the water current carries away feces and fluidizes the bed of seed with a gentle tumbling motion. As seed grow larger they can be packed into upwellers in greater volumes in a bed several centimeters thick. As the seed grow, the flow rate to each silo needs to be increased to provide adequate food and to keep the seed bed fluidized.

Screens on the wellers need to be regularly cleaned and checked for damage. The finer mesh screens on downwellers are especially delicate, prone to fouling, and will clog quickly with silt and feces. A small imperfection in a screen can allow thousands of spat to escape. As the animals grow they can be moved onto larger mesh screens, which are sturdier and less prone to fouling.

One approach to oyster culture is called "remote setting." Late-stage larvae are placed in large tanks that have been filled with bags of shell. After a few days, several larvae have set on each shell and the bags are moved into field nurseries. After a few weeks, the spat are well established and the shell is spread on the

growing grounds. Since several spat are growing on each shell, they often grow into each other, forming large, irregular clumps. Those that grow into irregular clumps are acceptable for shucking, but few would be considered suitable for the more lucrative half-shell raw-bar trade, where single, uniform, cupped oysters are more desirable. Hatchery operators have learned that single oysters can be produced by presenting oyster larvae with "micro-cultch," tiny chips of ground-up shell about 150 μm in diameter, only big enough to allow one or two larvae to attach to each fragment.

5.11 Nursery and growout scale considerations

To better understand the economic factors driving the various growout options, it is useful to consider the scale of operations. Data for the following example are gleaned from a New England oyster hatchery and growout operation (Rheault & Rice 1995). This is simply an example; growth rates will vary greatly depending on temperature, flow rate, stocking density, food quality, and shellfish species.

One million larvae can be grown in as little as 100 liters of water and subsist on a few liters of cultured algae a day. One million, 1-mm seed have a total volume of about two liters. At this size they can be held in a few small upwellers and fed with a few hundred liters of algae a day. In two weeks the same crop can grow to an average size of 3 mm, with a packed volume of about 12 liters, while food demands can exceed 1,000 liters of cultured algae a day. At this point (or earlier) it becomes imperative to wean the animals from cultured algae and offer them raw seawater so they can feed on natural microalgae and other organic particles.

This grower moves his seed to floating upwellers in early summer at a size of 1 mm. Each upweller silo is 60 cm square (360 cm^2), and food-rich water is pumped up at 200 to 400 Lpm. At this size, the oyster seed line the bottom of each silo in a layer that is 30-cm deep, tripling in volume each week. Over the next three weeks the oysters grow quickly in size and volume, growing to an average of 10 mm with a total crop volume of about 500 liters, overflowing 10 upweller silos. During this time, the seed need to be stirred daily, restocked every five to seven days, and graded by size every other week.

In the following three weeks growth slows somewhat, mean size reaches about 15 mm, and the total crop volume increases to about 3,600 L. This grower uses a modified rack-and-bag growout system with bags measuring 0.6 m by 0.6 m. Over this period the largest oysters are stocked into over 1,000 growout bags at two liters per bag, while the slower growers are retained in upwellers.

By the end of the first growing season the mean size approaches 35 mm, and the entire crop fills over 4,000 growout bags stocked at four liters per bag. Each bag is constantly getting fouled and needs to be cleaned and divided every one to two months. This grower field-plants his oysters on the bottom the following summer, freeing the bags that are needed for next year's crop. In the fall, he starts to harvest about one ton each week of eighteen-month-old, market-size animals (>75 mm). Harvest continues throughout the year, but feeding and

growth cease once water temperatures dip below 10°C (mid-November to May at this location). Slower growing animals may take another season to reach market size.

Production-scale intensive shellfish culture is essentially a massive materials-handling exercise, necessitating the handling of tons of live animals on a regular basis. Where labor costs are high, automation and mechanization are essential to keep operating costs down.

5.12 Nursery methods

The nursery phase of shellfish culture is arguably the most challenging. There is no best time to move seed from the hatchery to the nursery, and different growers will do this at different sizes. Hatcheries typically set the larvae inside and grow the spat up to several millimeters before they are moved out to nurseries. Because filtering seawater and feeding cultured algae is expensive, hatcheries try to shift over to raw seawater as soon as possible. If ambient temperatures allow it, the spat can be switched to raw seawater once they reach a few millimeters. This can be done on land in upwellers or raceways, or in the water in various types of containers.

5.12.1 Nursery culture: static systems, pearl nets, and rack-and-bag systems

The simplest approach to growing shellfish seed is to disperse them in the wild, but mortality rates for small, unprotected shellfish usually approach 100%. To protect the small spat, they are usually held in fine-mesh containers and suspended where natural water currents will keep them well fed. The Japanese were probably the first to attempt this at any significant scale using pearl nets and lantern nets. A pearl net is a pyramid-shaped container with a flat bottom and sloped walls made of a fine-mesh material. Spat are introduced through a slit on one side, the slit is sewn shut, and the pearl nets are suspended in food-rich waters until the spat are large enough to be moved to a larger-mesh container. Suspended and strung together in long chains, pearl nets look somewhat like a string of pearls. Many growers still use pearl nets to this day, especially for early life stages of scallops, but most growers have moved to other systems because pearl nets are labor intensive to load, sew shut, and later unload.

The next step after pearl nets is often the Japanese lantern net, so-called because it resembles a paper lantern (fig. 5.5). Lantern nets hold several tiers of shellfish on horizontal shelves up to 0.5 m in diameter, all protected by a cylinder of netting. Similar to pearl nets, shellfish are stocked into lantern nets through a slit on the side that is sewn shut. Novel lantern net designs use trap doors or Velcro to eliminate the labor-intensive sewing step.

Suspending culture systems from the surface from rafts or floats (typically on anchored long-lines) allows growers to utilize areas where the bottom is

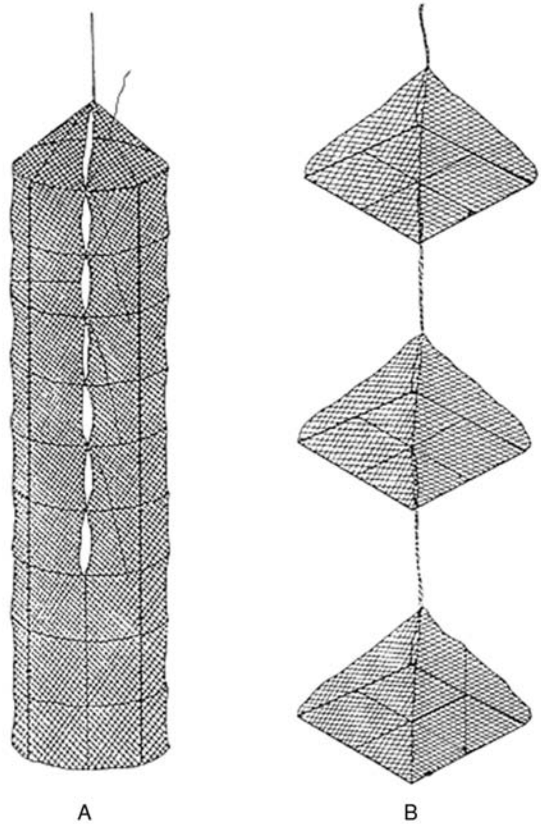

Figure 5.5 Lantern net. Photo courtesy of http://www.fao.org/docrep/field/003/AB739E/AB739E03.htm

not suitable or where benthic predators are too numerous. Surface waters are also usually warmer, with stronger currents and more plentiful microalgae—all conditions conducive to faster growth. Another advantage is that by utilizing the vertical dimension of the water column, growers can hold much greater numbers of animals per square meter of bottom.

A number of contraptions have been developed to hold and grow shellfish seed. Early efforts used wood, natural-fiber netting, or galvanized wire, but with the invention of synthetic fibers, plastic netting, PVC, and injection-molded plastics came a wide array of novel designs. Trays, pillow-shaped bags, and many other containers have been tried. Most of these can be lumped into the category of modified "rack-and-bag" systems. Bags can be floated at the surface, suspended from rafts, placed directly on the bottom or held off the bottom by trestles, cages, or racks (fig. 5.6). The mesh of the container needs to be fine enough to retain the seed, yet sturdy enough to resist the attack of crabs. The bottom of the container should be held flat so the seed don't all slide down into a pile. This would negate the advantage of having a container with a large surface area since the animals in the middle of the pile might starve or suffocate.

Figure 5.6 Bags on trestles. Photo courtesy of Robert Rheault.

Each of these nursery culture methods requires regular maintenance. Fine-mesh containers needed for smaller seed need the most frequent attention because the fine mesh will clog quickly with silt and fouling organisms, restricting the flow of water and food. As the spat grow they continually need to be thinned so that competition for food doesn't limit growth. Periodic sieving and grading is recommended because larger animals will tend to consume most of the food, and small seed will never grow to their full potential unless they are held separately.

Small seed can double or triple (or more) in volume each week, so the increase in total crop volume is geometric. As the seed get larger, their metabolism and growth rate slows so the stocking density (measured by biomass) can be increased, while the number of individuals per unit area drops. Larger-mesh containers have more open area so it takes longer for fouling organisms to colonize and occlude the openings; therefore the time between cleaning and restocking can be extended. But with every restocking, the number of containers needed to hold the crop increases geometrically.

5.12.2 Nursery culture: pumped systems, upwellers, and raceways

Raceways are a popular method of nursery culture. These are long, gently sloped, shallow tanks with water pumped into one end and flowing out at the other. Raceways need to be drained regularly to wash out any accumulated silt and feces. The stocking density is limited by total surface area of the tank, as the animals must be grown in a single layer. Corrugated plastic can be used in raceways to grow scallops or abalone, increasing the surface area for attachment.

In raceways, the animals at the front end will grow faster because they get more food than the animals near the drain.

Upwellers are one of the most effective nursery culture methods, but as the crop expands in volume, the silos need to be substantially larger and flow rates increased to ensure that the spat receive adequate food. The flow demands of a specific system will vary depending on the ambient food concentration, the species, and the biomass of the spat. Pumping costs quickly become a major economic concern.

The energy required to pump water is directly proportional to the "head pressure," which is determined by the length and diameter of the pipe and the vertical height that the water must be lifted. To reduce pumping costs growers move their nursery systems as close to the water as possible. Floating the upweller in the water reduces the head pressure to near zero, cutting pumping costs dramatically. Floating upwellers (FLUPSYs) have the additional advantage of not needing any expensive waterfront property.

5.13 Growout methods

As mentioned earlier, there is no clear division between nursery culture and growout. In theory, all of the same methods used for nursery culture of seed can be used to grow shellfish all the way to market size. From a practical standpoint, however, most of these systems become too expensive as the total crop volume expands.

Generally, growers try to limit the use of gear-intensive and labor-intensive culture methods to the nursery phase; once the seed reaches a size where it is resistant to most predators, seed can be broadcast on the bottom for growout to market size. There is theoretically a "size of refuge" that needs to be determined experimentally in each location by free-planting a range of seed sizes and monitoring survival. Larger seed will have a higher survival rate, but in most areas there is no size that guarantees shellfish will be predator proof. Each grower needs to determine at what size predation losses decline to acceptable levels. This is often referred to as "field-plantable" size, and it varies with species and with the predator assemblage at each location.

5.13.1 In-bottom or on-bottom growout

The simplest growout method involves broadcasting the seed on the bottom and letting it grow to market size. For clams and oysters, planting densities can vary from 300 to 1,500 per m^2, but optimal densities need to be determined for any given site. In cases where seed are inexpensive and mortality rates acceptable, this approach is economical and can be highly productive; however, most sites will suffer staggering predation mortality.

Intertidal clam farmers have learned that most predators can be thwarted with light plastic bird-netting rolled out over the seed at low tide and weighed down around the periphery. The netting comes in rolls that are 4.5-m wide with mesh sizes of 6 mm and 12 mm being the most commonly used. Maintenance consists of periodic inspections for damage to the net and removal of fouling during the two- to three-year growout period.

5.13.2 Rack and bag (subtidal or intertidal)

Various rack-and-bag systems are commonly used for both nursery culture and growout, with the only real distinction being that larger shellfish can be grown in larger-mesh bags. Again, these bags can be placed on the bottom or held off the bottom on trestles or in cages and racks; they can be used in subtidal or intertidal locations. Anything the grower can do to improve the flow of water through the mesh will increase the seston flux, resulting in faster growth, lower stress, and better condition index. Larger mesh takes longer to become fouled and will have less resistance to flow, so growers typically use the largest size mesh that will retain the seed and protect it from predators. Water will take the path of least resistance, with most of it tending to flow around the bag as opposed to through it. Shellfish held in a clean, 12-mm mesh Vexar (Conwed Plastics, LLC, Minneapolis, MN) bag will experience a 90% reduction in flow compared to animals just outside the bag (Rheault unpub. data).

Since current speed drops to zero right at the bottom, most growers try to keep their bags at least a few centimeters off the sediment. This allows better water circulation and keeps feces and silt from accumulating in the bags.

5.13.3 Suspended gear (fixed or floating): Taylor floats and lantern nets

As stated earlier, moving the gear higher up in the water column usually ensures better current flow, higher phytoplankton concentrations, and warmer water—all conducive to faster growth. Many growers use trestles or tables to hold their bags off the bottom in the intertidal zone where they are exposed for part of the tidal cycle. Since animals suspended from floats or rafts are able to feed continuously, floating gear is perhaps the best of all worlds for shellfish. Suspended gear allows growers to use areas where benthic conditions might not be suitable for bottom culture while keeping shellfish high in the water column and allowing them to feed continuously.

Growers have had success putting floats inside bags, attaching floats to the sides of bags, and fabricating all manner of floating rafts. Using huge rafts to hang long ropes of mussels has proven to be a successful approach for hundreds of years. The Japanese use rafts and longlines to grow scallops using a

Figure 5.7 Taylor float. Photo courtesy of Daniel J. Grosse.

technique called "ear hanging." By drilling a small hole in the shell of the scallop near the hinge (the ear), each scallop can be individually fastened to a larger rope. Recently, growers have developed machines to mechanize this otherwise laborious process.

A float design that has gained popularity in the mid-Atlantic region is the Taylor float (fig. 5.7). Constructed out of a ring of PVC pipe to provide floatation with a wire basket hung below, Taylor floats come in a variety of shapes and sizes and can hold several Vexar bags.

Floating gear can be susceptible to storm damage and is best suited for sheltered waters, which can pose permitting issues in areas where aesthetic considerations or navigation are important. In deep water another option is to hang gear near the surface from horizontal longlines. This is the preferred technique for growing mussels and scallops. State-of-the-art mussel farms have developed paired-backbone longlines, 100 to 200 m long, with large buoys capable of supporting a tonne or more, with 8-tonne anchors at either end (fig. 5.8). Mussel seed are injected into tubular mesh called "socks," which are suspended at regular intervals from the backbone lines extending 6 to 15 m below the surface. A typical New Zealand longline is about 110 meters long, holds around 3,000 meters of culture sock and produces around 25 tonnes of mussels in an 18-month rotation.

Scallop farmers use similar longlines, but instead of mussel socks they hang lantern nets. As the animals grow and the weight of fouling organisms on the

Figure 5.8 Mussel longlines. Photo courtesy of Richard Langan.

gear increases, the growers must either remove the fouling or add additional floatation to keep the whole operation from sinking. As scallops are sensitive to excessive movement, growers in sites exposed to excessive wave action will suspend the backbone lines below the surface so that the animals are insulated from all but the heaviest wave action.

More recently, growers have constructed longlines in intertidal waters by driving posts into the sediment and stretching cables between the posts. Injection-molded plastic baskets called Aquapurses (Tooltech PTY, Australia) clip on the cable and open like a clamshell to access the shellfish. The cables can be raised or lowered to adjust the time of air exposure needed to control fouling. Some species of oysters become adapted to a subtidal existence and when they are harvested they tend to gape; and once they become dehydrated and the gill dries out the animals soon die. By gradually raising the level where these oysters are grown, farmers are able to condition oysters to increasing periods of air exposure, which allows them to strengthen their adductor muscles so they maintain a tight seal while they are being shipped to consumers.

5.14 Fouling

Biofouling is a huge problem for shellfish growers because fouling organisms restrict the flow of water to the crop and often compete directly for food (Lesser *et al*. 1992). Severe fouling will reduce the condition index of the crop and can lead to mortalities. A recent national survey revealed that that biofouling control efforts can account for up to 20% of annual operating costs (gear-intensive floating or suspended-culture systems reported higher costs; Adams *et al*. 2011). In addition, encrusting organisms such as barnacles can detract from the visual appeal of the product, reducing the market value.

The principle fouling organisms include macroalgae, tunicates, sponges, barnacles, and other shellfish. Macroalgae can block the flow of water, but most are relatively easy to control and do not compete for food. In contrast, the many species of colonial and solitary tunicates (sea squirts) can pose significant challenges for growers. Some notable solitary tunicate species include the Asian stalked tunicate, *Styela clava;* the sea grape, *Molgula manhattensi;* the sea squirts, *Ascidiella aspersa* and *Ciona intestinalis*. Many of these are non-native, invasive species, thriving in new environments where there are few natural predators. They are all highly fecund, opportunistic filter-feeders with astounding growth rates, capable of coating the surfaces of any gear put into the water in a matter of weeks. Besides blocking flow and competing for food, heavy growths of tunicates can cause floating gear to sink and force growers to redesign handling gear to bear the added weight.

Barnacles (*Balanus* sp.) are another particularly nettlesome fouling organism and are difficult to control without killing the shellfish that they set on. In certain locales, oysters themselves can be fouling organisms, even when they are also the species in culture. Mid-Atlantic growers find that juvenile oyster overset on both their market-size adults and their culture gear interferes with growth and condition index, lowering the market value of the crop. Similarly, a heavy overset of mussels on culture gear can be devastating to the crop causing the producer to incur crippling removal costs.

Another fouling organism, the yellow boring sponge, *Cliona* spp., deserves special mention. In addition to competing for food and restricting the flow of water, this organism will encrust oysters and bore small holes into the shell by secreting acid. The labyrinth of holes weakens the shell, making the oysters more susceptible to predation. The oyster tries to secrete additional shell to protect itself, taking precious energy away from somatic growth. More importantly the holes reduce the market value of the oysters because the shell crumbles when shucked, leaving a nasty mess of shell fragments and yellow sponge in the meat.

5.15 Fouling control strategies

There are three basic approaches to controlling fouling: prevention, physical removal, and slaughter. Prevention can be done by physically avoiding the larvae

of the fouling organisms, providing one can predict when and where sets of these organisms occur, but this is rarely practical. More commonly growers have tried various nontoxic antifouling coatings that discourage the settlement of invertebrate larvae. Removal techniques include pressure washing with high-pressure water, physically brushing, scraping, or scrubbing off the fouling, all of which are costly and labor intensive.

There are various approaches to killing fouling organisms on the crop and on the gear. Killing the fouling community without having to remove the shellfish from the gear obviously saves a lot of effort, but killing the fouling organisms without killing the crop can be a challenge. Air-drying is one of the most common approaches, especially for oyster growers who work in intertidal sites. By adjusting the height of the gear, growers can find the right exposure time that kills most of the fouling, but not the oysters. Growers who use intertidal rack-and-bag techniques usually flip the bags periodically, letting the sun do the work of killing the soft-bodied invertebrates. To kill tougher fouling organisms such as barnacles, oyster overset, or mussels it is usually necessary to restock the crop in clean gear and allow the fouled gear to dry out for several days.

Dipping oysters in their containers into a saturated brine solution for several minutes is another effective method of killing macroalgae and soft-bodied invertebrates, but to control boring sponge or mud blister worms (*Polydora websterii*) the dip needs to be followed by an extended period of air-drying to further concentrate the salt (MacKenzie & Shearer 1959). This method can also be effective for controlling very small oyster overset and barnacles, but once these fouling organisms reach a few millimeters in size they will tolerate the treatment (Debrosse & Allen 1993). Brine dipping and air-drying cannot be used to control fouling on scallops because their valves do not form a watertight seal.

Spraying with, or dipping in, acetic acid, hydrated lime, or chlorine can also be an effective control method for tunicates (MacKenzie 1977; Forrest *et al.* 2007), but the application of harsher chemicals may not be suitable for use on food or in the marine environment. Some growers have experimented with various means of biological control, reporting some success with placing a few killifish (*Fundulus heteroclitus*) or periwinkles (*Littorina littorea*) inside each tray or bag so they can graze on the fouling.

5.16 Predation

It seems as if almost everything likes to eat shellfish, and smaller seed are especially highly vulnerable. Planting unprotected, 1-mm seed is like ringing a dinner bell. Many species of crabs are quickly attracted to such plantings and won't leave until they reduce densities to background levels (Arnold 1984). As the seed get larger they will sometimes be able to resist attack by small crabs, or at the very least it will take the crabs longer to eat the crop. Some predators such as starfish (*Asterias* sp.) or the oyster drill (*Urosalpinx cinerea*) can attack adult shellfish several times their own size. Some growing areas are plagued by large predatory snails such as the whelks *Busycotypus* spp. (formerly *Busycon*), moon

snails *Neverita duplicatus* and *Euspira heros,* or the cow nose ray (*Rhinoptera bonasus*), all of which can take market-size shellfish.

Even protecting the shellfish behind protective netting cannot guarantee that the predators won't take their share. Free-swimming larvae of some snails, crabs, and the oyster flatworm, *Stylochus ellipticus,* may settle inside the containers, sometimes growing fast enough to consume most of the contents. Starfish can evert their stomach, pushing it through 12-mm mesh Vexar bags to externally digest the shellfish in the bag while remaining on the outside. It may take several days to consume an oyster this way, but over a period of months the losses can be catastrophic. Growers need to be vigilant, learning about the various predators that afflict their particular growing area and developing appropriate strategies to combat each foe.

Mussel farmers can suffer severe losses from flocks of diving ducks such as the Scoter (*Mellanitta nigra*) or Eider duck (*Somateria mollissima*). These ducks, along with waders like the Oystercatcher (*Haematopus ostralegus*), can wreak havoc on unprotected clam and oyster seed.

Predator control strategies may include sweeping the ground clean with a hydraulic dredge before planting, placing baited traps (effective for starfish, whelks, and crabs), or mopping (dragging weighted cloth mops over the grounds to entangle starfish). Growers have also experimented with barrier fencing to exclude cow nose rays or whelks, and enclosing mussel rafts with netting to exclude diving ducks.

But the most pernicious and cunning predators of all are humans. Shellfish poachers are inventive and persistent, and they often cause tremendous damage as they "help" growers harvest their crops. Trapping and eliminating human predators can be expensive and time consuming.

5.17 Harvest

Shellfish farmers have several advantages over wild fishermen when it comes to harvesting. The farmers know where to find their crops and the densities are usually much greater than for wild stocks. Farmers are not typically constrained by harvest regulations designed to preserve wild stocks such as seasonal restrictions, bag limits, quotas, possession limits, harvest methods, or minimum size. While wild-harvest fishermen often resent this double standard, it makes little sense to enforce these restrictions on farmers who plant and own their crops. The harvest methods of a culturist rarely have a negative impact on wild populations. Sometimes enforcement authorities will insist on maintaining some restrictions, such as minimum size, because they cannot differentiate cultured product from wild and they believe relaxing the restriction for one group would invite unscrupulous wild harvesters to apply for aquaculture leases, simply so they can land sub-legal wild shellfish.

Shellfish farmers are also free from the "race to fish" tendency of quota-managed fisheries (FAO 1997). When fishermen are managed by a quota that they do not own, they are highly motivated to fish as fast as they can until

the quota is filled and the fishery is closed. This results in short seasons and huge fluctuations in supply, which, in turn, causes huge fluctuations in price. In contrast, farmers are able to modulate their harvest to meet demand or to optimize price, quality, or yield.

Since shellfish are often sold live and fresh for raw consumption and since they are highly perishable, farmers have the added advantage of being able to harvest only what they need to meet immediate demand. They can effectively stockpile product in the water under optimal conditions, delivering product to the market that has been harvested that day instead of stockpiling inventory in coolers.

Shellfish farmers who use container culture are able to simply pull up their gear, select the market-sized individuals, and return the smaller ones to the water for additional growth. This means growers are able to provide a more uniform cull than wild harvesters. Growers who have opted for bottom planting typically use traditional harvest methods such as rakes, dredges, or hand-picking at low tide. This description makes it sound easy, but once farms develop to a significant scale, the work becomes an exercise in materials handling on an epic scale. Tonnes of shellfish must be handled on a weekly basis, taking care to keep the animals alive, undamaged and wholesome. Harvesting efforts can easily comprise 30% of operating costs. Mechanization can be critical to success, especially where labor costs are high. New Zealand mussel farmers have developed vessels and equipment capable of harvesting more than twenty tonnes in a single day with a crew of three. Clam farmers in the Pacific Northwest and Europe have modified small tractors designed to harvest tulip bulbs to cut their harvest costs by more than 80% (W. Dewey pers. comm.).

5.18 Food safety

Since shellfish are filter-feeders that can accumulate pathogenic viruses and bacteria from the water, and since they are often destined for raw consumption, there is a greater potential for food-borne illness outbreaks with shellfish than with many other foods. In the United States the Food and Drug Administration's National Shellfish Sanitation Program (NSSP) has established stringent regulations to minimize the risks associated with raw molluscan shellfish consumption (FDA 2009). The NSSP sets forth guidelines for the bacteriological monitoring and designation of harvest areas; depuration of product from uncertified waters; and the processing, handling, and transportation of molluscan shellfish. Most other countries have shellfish sanitation programs that are equivalent or similar to the NSSP.

Once the shellfish is harvested it is important to ensure that it is protected from temperature extremes and placed into refrigeration as soon as possible. At elevated temperatures bacteria can multiply rapidly, going from safe concentrations to unsafe levels in a matter of hours. However, freezing or even cooling shellfish too quickly can kill shellfish, and when they thaw they will gape, dry out, and begin to decay. In the United States all processing of shellfish must be

done in accordance with a Hazard Analysis and Critical Control Point (HACCP) plan designed to identify and eliminate potential sources of contamination and protect the product from temperature abuse (FDA 2005).

5.19 Shellfish diseases

Historical records are replete with descriptions of mass mortalities and shellfish epizootics afflicting practically every species of shellfish, but none of these shellfish diseases are known to affect humans. Bivalves are susceptible to cancers (neoplasia), bacterial diseases (vibriosis), and viral diseases (herpes virus), as well as a wide variety of protozoan parasites that can devastate the crop and wild populations. To list all of the diseases, symptoms, and causative agents is beyond the scope of this chapter; however, Bower and McGladdery (1997) catalog over 150 diseases of commercially exploited mollusks.

It is important to differentiate between infection and disease. Many organisms may carry an infection without ever showing the clinical signs of disease. Some protozoan infections may not cause significant problems for years. Whether an infection becomes a disease is determined by the virulence of the pathogen, the susceptibility of the host, and other environmental factors.

While some diseases are found in the hatchery or may only affect young seed, the most devastating epizootics seem to be associated with protozoan parasites. Low-level infections may persist for years without ever causing significant mortalities, but under the right conditions they can proliferate and wipe out a crop in a matter of months. Pathological examination often reveals a number of parasites that are apparently living off the shellfish benignly, causing little harm to the host. There are, however a few notable parasites that have killed billions of shellfish, both wild and cultured.

There are several examples where a native oyster population has been driven to near extinction by disease. The native European flat oyster (*Ostrea edulis*) was all but eliminated by the protozoan *Bonamia ostraea*, forcing the European industry to import *Crassostrea gigas,* which is now the dominant oyster produced in Europe. In the mid-Atlantic region of the United States the parasites MSX (*Haplosporidium nelsoni*) and Dermo (*Perkinsus marinus*) have reduced the populations of the native Eeastern oyster to less than 1% of historical levels, causing regulators to consider listing the species as threatened.

5.20 Disease management options

Many epizootic outbreaks can be traced to the early practices involving the indiscriminate movement of shellfish between growing areas. Once this was recognized, growers and regulators backed the development of regulations mandating the pathological inspection of seed stock before it can be transported across state lines, and quarantine procedures to govern international transport of broodstock. Strict adherence to these regulations is the best way to minimize

the risk of introducing diseases to new areas and is perhaps the best defense against new epizootic disease outbreaks.

Many diseases are already endemic in many growing areas around the world, and growers do what they can to manage around them. Diseases are often exacerbated by stressors such as overcrowding, pollution, poor nutrition, hypoxia, and temperature shock. In some cases mortalities can be reduced by thinning the crop, increasing flow rates, or simply by maintaining good hygiene. With progressive diseases growers can sometimes harvest before mortalities become too severe. Some parasites are intolerant of low or high salinities and mortalities can be avoided by moving the crop to appropriate waters.

Because shellfish have primitive immune systems it is unlikely that efforts to develop vaccinations to stimulate immunity will ever be successful. Also, once the animals are moved out of the hatchery it becomes impractical to deliver any type of drug or antibiotic. It appears that the best hope of improving resistance to disease lies in a long-term, coordinated, selective breeding program. The industry is working to develop lines that are not only disease resistant, but also fast growing and adapted to the very different environments across the species' entire range.

5.21 Genetics: selective breeding

The principal function of the hatchery is to allow growers to control the life cycle of an animal, from egg to adult, and back to egg again. This process is referred to as domestication. Many agricultural species have been domesticated for thousands of years, while others such as shellfish, for mere decades. Closing the life cycle in hatcheries invariably results in some measure of change in the genetic structure of the population because the process selects for animals that do well in hatchery conditions. Most hatcheries also select broodstock for traits such as fast growth, better meat yield, specialized coloration, disease resistance, and shell shape. Many culturists have worked for several generations to develop "strains" adapted to the conditions unique to their particular growout site.

By agricultural standards, professional shellfish breeding programs are in their infancy. The longest running professional breeding program is located at the Haskin Shellfish Research Lab, where attempts to select for resistance to MSX disease in *C. virginica* were begun by Dr. Hal Haskin in the late 1950s. There are now several MSX-resistant oyster strains being developed that are the living legacy of his work. In the last 20 years, breeding programs for the Pacific oyster, *C. gigas,* have also been established in the Pacific Northwest, Australia, and France, focusing on growth characteristics and resistance to summer mortality.

Sometimes selective breeding can have unintended consequences. In the process of selecting for a trait such as fast growth, hatcheries run the risk of narrowing the genetic diversity of the population and potentially eliminating some desirable trait such as resistance to disease. To avoid genetic bottlenecks some hatchery operators try to maintain genetic diversity by performing periodic

out-crosses with wild populations and then performing back-crosses among the progeny to ensure that the desirable traits are not diluted.

5.22 Triploidy

In the 1970s researchers at the University of Maine demonstrated that shellfish could be induced to retain an extra set of chromosomes (Stanley *et al*. 1981). The vast majority of sexually reproducing organisms are referred to as "diploid" because they hold two sets of chromosomes, one inherited from the father's sperm and another from the mother's egg. For example, each human cell has two sets of 23 chromosomes for a diploid chromosome number of 46. Oysters have only 10 chromosomes and have a diploid chromosome number of 20. Triploid oyster cells have three sets, or 30 chromosomes. Only plants and lower animals, such as amphibians, fish, and mollusks, can tolerate the triploid condition.

Triploid animals are reproductively sterile, which prevents them from expending energy on forming eggs and sperm. Most bivalve species devote a considerable portion of their energy budget to the formation of gametes. Right before and right after spawning, shellfish can have an undesirable texture, being either fat and milky or thin and watery. Culturists find that triploids don't "waste" energy on reproduction so they grow faster, have improved marketability, and are generally more robust.

Today, only oysters are widely cultivated as triploids, since the process of making triploids has not yet been perfected for other shellfish taxa. Triploid oysters were first used commercially in the mid-1980s in the Pacific Northwest, but the process was not widely adopted because of difficulties scaling up the procedure for making triploids. This changed with the development of tetraploid oysters—those with four sets of chromosomes (Guo *et al.* 1996). For reasons not discussed here, tetraploids are fertile and produce sperm containing two sets of chromosomes, called di-haploid. When tetraploid sperm are used to fertilize normal (haploid) eggs, triploids result. Tetraploids have been used to make triploids in both *C. gigas* and *C. virginica,* and triploids now make up a substantial percentage of oyster production in the Pacific Northwest, France, and increasingly, the mid-Atlantic (Nell 2002).

Triploidy is also a valuable tool for culturists hoping to limit genetic interaction between cultured animals and wild populations. Sterile triploids were used in recent studies evaluating the ecological issues surrounding the proposed introduction of non-native *C. ariakensis* into Chesapeake Bay.

5.23 Harmful algal blooms

There are many species of phytoplankton that produce toxins and noxious substances. Often referred to generically as "red tides," a more appropriate term to encompass the wide range of species involved is "Harmful Algal Blooms" (HABs; reviewed by Shumway 1990). Shellfish will accumulate the algal toxins

and when eaten by humans, the toxins can cause paralysis, amnesia, and a number of other maladies. HABs can also impact the shellfish themselves by interfering with filtration, or occasionally causing mass mortalities and set failures (Shumway *et al*. 2006; Hégaret *et al*. 2007).

Unfortunately, there is virtually nothing that can be done to prevent or disperse an algal bloom. At best, the toxin is detected and the harvest areas are closed before anyone gets ill. A temporary disruption in harvest and sales is easier to endure than a reputation sullied by illness (or death) associated with one's product. Blooms usually pass after a few weeks and the toxin in the tissue usually dissipates shortly thereafter, but in some species the toxins may persist for years (Bricelj & Shumway 1998; Hégaret *et al*. 2008). Unfortunately, the only management approaches available to growers are to select growing areas with infrequent HABs and to monitor for toxins in the tissues, since moving the crop to a different location is rarely a viable option.

5.24 Site selection

Perhaps the single most important decision facing a prospective grower is where to place the farm. As mentioned previously, the most important factors regulating growth are temperature and seston flux (the product of current speed and phytoplankton concentration). Within a region, temperatures are likely to be similar, but current speed and phytoplankton concentration can each vary tenfold over very short distances, resulting in huge differences in growth rates and in optimal stocking densities. Significant growth differences can sometimes be measured between sites that are 100 meters apart, usually because of physical features impacting the current profile. Rather than deploying expensive current meters and taking phytoplankton samples, perhaps the best way to evaluate and compare sites is to deploy small experimental cages for a growing season. Let the shellfish do the math of integrating the sinusoidal current speed function with the seasonal and diurnal phytoplankton data.

After seston flux, the next most important site characteristic is typically the predator assemblage. It makes little sense to broadcast shellfish seed in areas where they will await certain death. Conversely, why spend money on expensive gear if free-planted seed have good survival rates? Determining the predators specific to a site is a matter of trial and error with a few kilometers (or parts per thousand of salinity) potentially making huge differences in which predators are abundant, which diseases are a problem, and what survival rates can be expected.

Increasingly, hypoxia (low dissolved oxygen concentration) is becoming a concern in many coastal growing areas, especially those in shallow sheltered waters with excess nutrient inputs. The same phytoplankton that produces oxygen during the day and makes good shellfish food will consume oxygen in the dark, potentially depleting oxygen to dangerous levels. When algal cells die and sink to the bottom, bacterial decomposition will cause further oxygen depletion. Since oxygen solubility decreases in warmer waters, calm summer nights are most

susceptible to hypoxic events. Most shellfish can tolerate a night of hypoxia, but some species are more susceptible than others, and repeated hypoxic events will lead to stress, impaired growth, and may cause mortalities.

Another consideration when choosing potential culture sites is the exposure to wind and waves. Sites with too much exposure will not be accessible for many days of the year and gear will need to be engineered to handle the forces associated with significant wave heights. Protected sites allow farmers to work with smaller boats, and can limit storm damage to gear and crops.

In an ideal world, growers would base their site selection decision on water quality and environmental parameters alone, but other factors, such as ease of access, distance from commercial dock space, and user conflicts, typically take precedence. Many growout sites have conflicts with other users of the marine resource, who may perceive a proposed shellfish farm to be a navigation hazard or a displacement of commercial or recreational fishing activities. Waterfront homeowners may object to the visual impact of the farm, or the potential for noise or lights while harvesting or processing. These types of user conflicts sharply constrain the choices of those wishing to farm shellfish. Federal law prohibits disturbing eelgrass beds because eelgrass has been designated as essential fish habitat. Similar laws protect endangered or threatened species that may use a desired site.

5.25 Carrying capacity

A significant concern relating to site selection is the cumulative impact of large populations of shellfish on primary production and other organisms in the local environment. Small-scale shellfish aquaculture has been shown to have many environmental benefits (Shumway *et al*. 2003), but excessive densities of shellfish can have adverse consequences (reviewed by McKindsey *et al*. 2006a). The intensity level of shellfish farming that starts to yield undesirable impacts is referred to as the "carrying capacity," and several carrying capacity terms have been defined depending on the impacts of concern (Inglis *et al*. 2000; Crawford *et al*. 2003; McKindsey *et al*. 2006b; Ferreira *et al*. 2007).

Farms that utilize large vertical arrays and suspended longlines can greatly increase the density of animals per m^2 compared with bottom-planted shellfish. Excessive food-competition can deplete local food supplies to a point where growth rates slow and shellfish on the farm have reduced meat yields. Further increases in planting density beyond this point no longer increase yield. This level is referred to as the "production carrying capacity" (Inglis *et al.* 2000). Once densities start to impact production, growers have a strong economic motivation to reduce densities, so examples of farms exceeding the production carrying capacity are rare and short-lived.

Dense populations of shellfish can cause the accumulation of fecal material on the bottom, potentially overwhelming the capacity of the environment to assimilate the organic matter, leading to local hypoxia and reduced diversity (Kaiser *et al.* 1998). This level is sometimes referred to as the "ecosystem carrying

capacity" (Crawford *et al*. 2003). More recently, resource managers have turned their attention to the impacts of shellfish culture on other organisms, the structure of the food web, and nutrient cycles. The point at which these impacts start to occur is referred to as the "ecological carrying capacity" (McKindsey *et al*. 2006b).

To determine the production carrying capacity is an empirical exercise in monitoring the condition index and growth rates of the animals on the farm. Determining the assimilative carrying capacity involves extensive monitoring of characteristics such as benthic oxygen demand and diversity. Predicting the ecological carrying capacity involves complex mass balance modeling with data inputs that describe the biomass and production of every significant food web element as well as measurements of nutrient inputs and water current dynamics (Jiang & Gibbs 2005). A relatively simple first-order estimate can be made by comparing the total filtration capacity of the shellfish population with the residence time of water in a given embayment. If the cumulative filtration capacity of shellfish in an area exceeds the flow of seston to the area, then the system is more likely to be dominated by filter feeders, increasing the potential for carrying capacity issues (Dame & Prins 1998).

5.26 Permitting challenges

The number and types of permits required for shellfish culture vary greatly. Most applications will have elements of local, state, and federal authority that need to be addressed. In the United States, some states delegate lease permitting entirely to the towns while some have centralized permitting authorities. It is usually easier to navigate centralized permits because local authorities are more easily swayed by the often passionate and vocal pleas of "not in my backyard." Opponents will usually claim that they support shellfish aquaculture, but they believe that the proposed site is not appropriate. Since claims that the proposed farm may impair the view are rarely convincing, opponents will often suggest that the proposed farm has some sort of undesirable environmental impact.

Fortunately, there is a growing body of evidence that shellfish farms are environmentally benign or beneficial to the environment (Shumway *et al.* 2003). Shellfish filter all types of particles from the water, enhancing light penetration and reducing turbidity. The presence of shellfish, and the gear used to grow them, increases the productivity and the biodiversity of an area (DeAlteris *et al*. 2004). Shellfish aquaculture is usually supported by environmental groups because farming methods use no drugs, chemicals, or feeds. In the United States, shellfish farms are widely recognized as a sustainable method of food production with tangible environmental benefits (Seafood Watch 2008).

Permitting can take months or years depending on the municipality and their familiarity with the issues. Shellfish lease permits usually require consultation and approval from the Army Corps of Engineers (for navigation concerns), NOAA (for essential fish habitat designation and endangered or threatened species concerns), the Environmental Protection Agency (to address water quality issues),

local or regional Fisheries Management Councils (to assess conflicts with commercial fishing), and local user groups (to evaluate recreational fishing and boating conflicts). This is not an exhaustive list, but it gives one an idea of what is involved. Some states have set up pre-permitted aquaculture zones that streamline the application process, but confine the applicant to predefined locations and methods of culture.

5.27 Non-native species

Over the past century there have been a great number of introductions of non-native shellfish species for aquaculture production. Fisheries managers, anxious to increase production when local stocks became depleted, borrowed a page from terrestrial agriculture and brought in novel shellfish from other regions. Most of our major terrestrial food crops and domesticated animals are introduced species, so introducing new shellfish species seemed to be a natural choice (Carlton 1992).

More recently, resource managers have become more cautious and tried to slow the spread of non-native species because of the potential for disastrous unanticipated environmental consequences (Carlton & Ruiz 2005). While many intentional introductions of exotic shellfish were successful, the majority failed to produce established populations. The most prominent example is the Japanese oyster, *Crassostrea gigas,* which now reigns supreme as the single most cultured species on the planet (FAO 2007). *C. gigas* was introduced on the West Coast of North America in the 1800s after fisheries and pollution decimated their native oyster, the delicate Olympia, *Ostrea conchaphelia*. Seed of *C. cigas* were shipped from Japan packed in seaweed, and several other species were inadvertently introduced in the process. The Manila clam first showed up on the West Coast in the 1930s and now Manila clams and *C. gigas* make up the vast majority of the cultured shellfish harvested in the Pacific Northwest. Other hitchhikers in these seed shipments included two notable pests: the green crab, *Carcinus maenas,* and the stalked tunicate, *Styela clava* (Carlton 1992).

The catastrophic environmental and economic impacts of a number of unintentional introductions have caused resource managers around the world to become more cautious about intentional species introductions (Carlton & Ruiz 2005). The International Council for the Exploration of the Sea has established strict protocols for moving species intended for culture across international boundaries in an attempt to limit unintended consequences (ICES 2005). Most states have implemented strict regulations prohibiting the introduction of non-native species, and responsible growers in the United States have established Best Practices governing interstate transport of seed and shell stock. These measures are designed to limit the risk of spreading hitchhikers, non-native species, and diseases beyond their existing ranges.

Despite these reservations there is still a motivation to introduce novel shellfish species for aquaculture. In the mid-Atlantic region there has been a push by some states to introduce the Suminoe oyster *Crassostrea ariakensis* to replace the

native *C. virginica,* whose stocks have been depleted by disease, overharvesting, and environmental degradation. This potential introduction was studied by a multidisciplinary team of National Academy of Sciences researchers who, after five years, decided that such an introduction "posed unacceptable ecological risks" (ACOE 2009).

5.28 References

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